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INVESTIGATING THE ROLE OF ADVECTION PROCESSES IN IMPROVED MARTIAN DUST ASSIMILATION TECHNIQUES FOR EXOMARS

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Introduction:

Mineral dust is a vital component of the martian weather and climate system. Its presence heats the atmosphere, at the same time causing cooling at the surface. While dust storms occur on Earth as well, Mars' lack of oceans and significantly lower thermal inertia means that the storms there can last up to weeks, rapidly reach global scale, and cause greater temperature variations (Haberle, Conway, & Pollack, 1982) (Read, Lewis, & Mulholland, 2015). Understanding martian dust's characteristics and transport is therefore key for planning and conducting future activity on Mars.

A valuable new source of dust observations will be soon be available following the successful orbital insertion of ExoMars' Trace Gas Orbiter (TGO), which will begin its science phase in March 2018. TGO will provide higher resolution vertical profiles of the atmosphere in general, and of atmospheric dust opacity in particular, especially from the ACS and NOMAD instruments. These observations will be integrated with the Open University's existing Mars General Circulation Model (MGCM) using a technique called data assimilation, which can constrain the model and help obtain the best possible representation of the Martian atmosphere (Lahoz, Khattatov, & Menard, 2010). Fig.1 illustrates the power of this technique in reconstructing atmospheric states from irregular data. Data assimilation techniques will be tested and validated using existing observations from the Mars Climate Sounder (MCS), in preparation for use with TGO data.

Previous work:

Current data assimilation schemes use observations from the Thermal Emission Spectrometer (TES), the Thermal Emission Imaging System (THEMIS), and the Mars Climate Sounder (MCS). Fig. 2 is an example of results from an assimilation of TES dust optical depth, assimilated with an analysis correction scheme adapted from the Met Office (Lorenc, Bell, & Macpherson, 1991) and using persistence forecasting, in which the dust field is kept constant when no direct observations are available (Lewis et al., 2007). Even with the irregular coverage and observations from the aerobraking phase of TES, with its orbital period of a day, data assimilation allows for the creation of a globally self-consistent atmospheric model, and therefore for the inference of non-observed variables such as wind speed. A further example of this is Fig. 3, which demonstrates a verti-

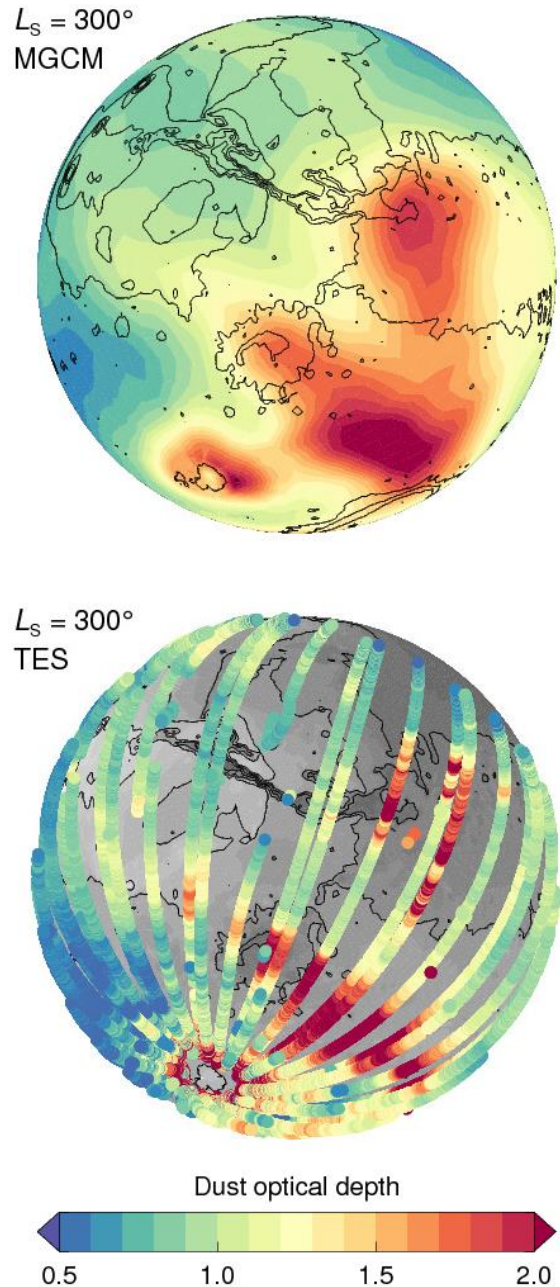


Figure 1: Top panel: total dust visible optical depth output for MGCM with TES dust data assimilated over a 5-sol period centred on $L_s = 300$, MY 26. Bottom panel: total dust visible optical depth observations from TES over the same period. The grey shading indicates topography.

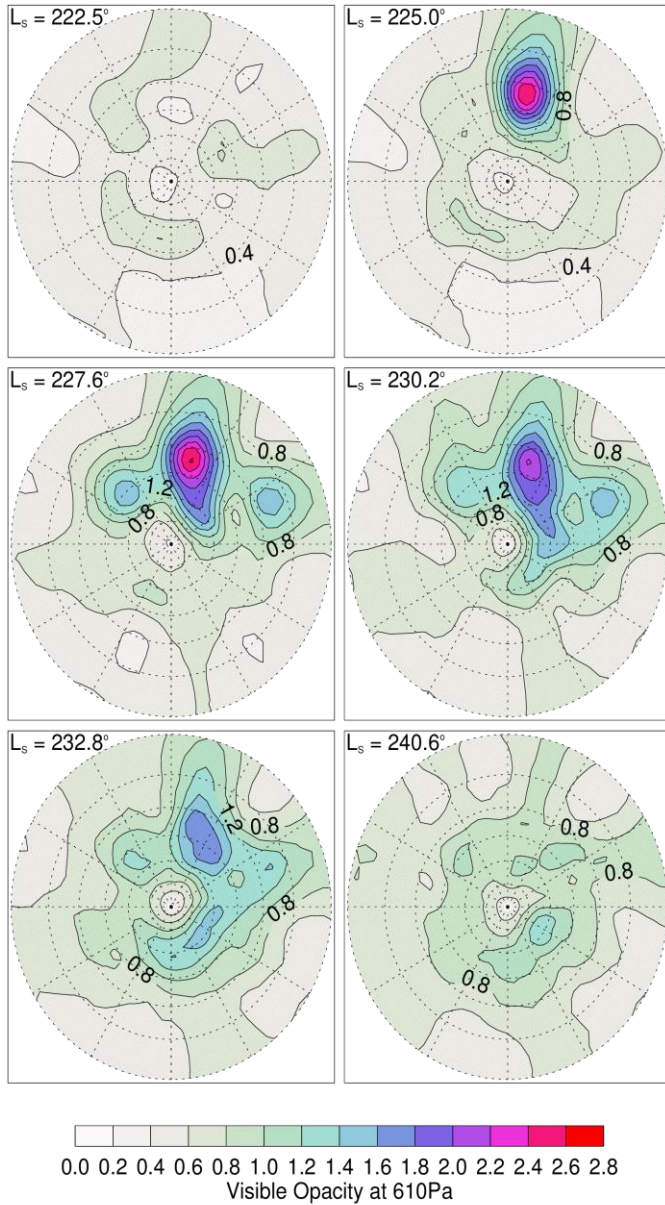


Figure 2: Total dust visible optical depth from the model assimilation, normalized to 610 Pa to remove topographic effects, for a sequence surrounding the onset and decay of the Noachis dust storm. Reading from upper left to lower right the intervals between the plots are 4, 4, 4, 4 and 12 sols. The plots are polar stereographic with the south pole at the centre, the equator at the edge, the prime meridian pointing upward and a grid spacing of 15 in latitude and 30 in longitude. (Lewis et al., 2007)

cal dust profile constructed by allowing dust transport in the MGCM but scaling the results to match total dust visible optical depths observed by TES and THEMIS. While TES/THEMIS data itself only gives a patchwork of total dust opacities, using the data to constrain dust transport can reproduce some important features of the Martian climate; for example, the collar of low dust density at approxi-

mately 60 degrees latitude matches where the south to north meridional circulation descends to the surface (Read, Lewis, and Mullholland, 2015).

While valuable, TES observations have limitations in the vertical which restrict the use of more realistic dust transport schemes. Currently, only MCS conducts significant limb observations from which vertical profiles can be reconstructed, but they often lack valid values for dust opacity near the Martian surface (Montabone et al., 2015). This relative paucity of vertical dust distribution measurements contributes to the fact that most assimilation schemes and dust scenarios are 2D only, working with the horizontal distribution of column dust optical depth (CDOD) and using the standard Conrath distribution to model vertical opacity, which assumes well-mixed dust (Conrath, 1975). However, observations from TES and MCS have confirmed the existence of discrete dust layers of enhanced opacity, suggesting that the well-mixed assumption does not necessarily hold (Guzewich et al., 2013).

In addition, to date dust advection has been treated simply in attempts to assimilate Martian data. For example, the current Mars Analysis Correction Data Assimilation Database (MACDA), as well as analytically prescribing vertical dust distribution, does not use the MGCM's ability to lift and transport dust to assimilate observations. Instead, it uses a persistence forecasting approach for the dust field (Montabone et al., 2014). Montabone et al.'s 2015 dust climatology uses spatial kriging with a time-dependence to represent possible dust motion during delays between observation times, but likewise does not include a dust transport model (Montabone et al., 2015). Greybush et al. conducted an ensemble-based reanalysis of TES thermal profile data, but using a dust field prescribed to vary seasonally rather than by fully assimilating dust opacities from TES (Greybush et al., 2012). Navarro et al. successfully reproduced detached dust layers without relying on the Conrath assumption; however, dust distributions were estimated by assimilating thermal profile observations (Navarro et al., 2014).

Proposed work:

Some work has already been done by Ruan et al. using 2-D data assimilation with full transport of the dust mass mixing ratio, yielding improved representation of the top of the atmospheric dust layer (Ruan, Montabone, Read, & Lewis, 2012). Further work by Ruan et al. explicitly advects dust while using MCS vertical profile data to track dust storms, yielding new results not apparent from the data or MGCMs alone; for example, the ability of storms to transport dust up to 30 km during their evolution (Ruan et al., this meeting). While simple statistical methods for assimilation such as gridding may be easier and more

generally applicable (Montabone et al., 2015), the results from Ruan and others suggest that more realistic dust advection schemes are a promising avenue for further research; especially in preparation for new TGO data, and to replicate results such as detached dust layers in the upper atmosphere.

However, the question of how exactly to fully couple winds and dust distribution remains an area open for investigation. Some possible methods of modelling dust transport and coupling dust metrics/parameters to wind will be tested on the MGCM and compared with existing assimilation schemes and free-running simulations, with an eye (following Ruan) to a fully 3-D dust assimilation. This would allow for the full exploitation of current and future vertical profiles. A further aim for this project would be to extend the wind-dust coupling to predict dust lifting through surface wind stress and/or dust devil activity. Model uncertainties and robustness can be estimated through ensemble forecasting. A realistic, coupled advection scheme for dust data assimilation combined with greater observational coverage could offer new insights into Martian dust transport and atmospheric behavior.

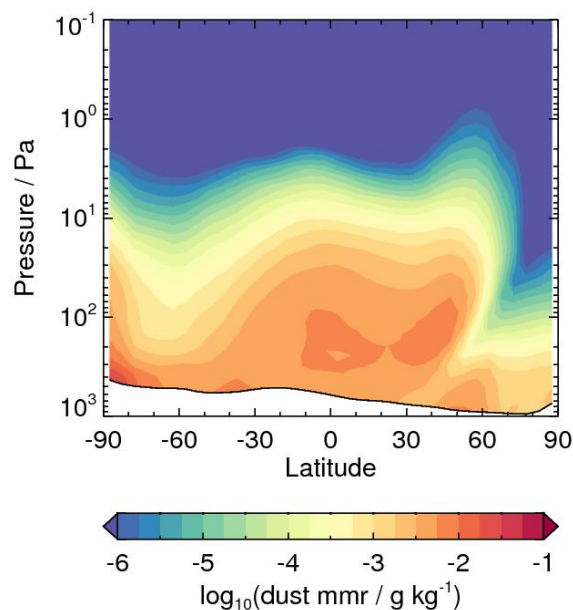


Figure 3: Zonal- and temporal-mean dust mass mixing ratio (averaged over same time period as Fig. 1), taken from an MGCM in which dust is transported but scaled to match the TES/THEMIS dust optical depth maps of Montabone et al. (2015). The black line at the bottom of the plot indicates the zonal-mean surface pressure.

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References:

- Conrath, Barney J. 1975. "Thermal structure of the Martian atmosphere during the dissipation of the dust storm of 1971." *Icarus* 36-46. doi:10.1016/0019-1035(75)90156-6.
- Greybush, S. J., R. J. Wilson, R. N. Hoffman, M. J. Hoffman, T. Miyoshi, K. Ide, T. McConnochie, and E. Kalnay. 2012. "Ensemble Kalman filter data assimilation of Thermal Emission Spectrometer temperature retrievals into a Mars GCM." *J. Geophys. Res.* doi:10.1029/2012JE004097.
- Guzewich, S. D., E. R. Talaat, A. D. Toigo, D. W. Waugh, and T. H. McConnochie. 2013. "High-altitude dust layers on Mars: Observations with the Thermal Emission Spectrometer." *J. Geophys. Res. Planets* 1177-1194. doi:10.1002/jgre.20076.
- Haberle, R. M., C. B. Conway, and J. B. Pollack. 1982. "Some effects of global dust storms on the atmospheric circulation of Mars." *Icarus* 322-367. doi:10.1016/0019-1035(82)90129-4.
- Lahoz, W., B. Khattatov, and R. Menard. 2010. *Data Assimilation: Making Sense of Observations*. Berlin: Springer.
- Lewis, S. R., P. L. Read, B. J. Conrath, J. C. Pearl, and M. D. Smith. 2007. "Assimilation of Thermal Emission Spectrometer atmospheric data during the Mars Global Surveyor aerobraking period." *Icarus* 327-347. doi:10.1016/j.icarus.2007.08.009.
- Lorenc, A. C., R. S. Bell, and B. Macpherson. 1991. "The Meteorological Office analysis correction data assimilation scheme." *Q. J. R. Meteorol. Soc.* doi:10.1002/qj.49711749704.
- Montabone, L., F. Forget, E. Millour, R. J. Wilson, S. R. Lewis, B. Cantor, D. Kass, et al. 2015. "Eight-year climatology of dust optical depth on Mars." *Icarus* 65-95. doi:10.1016/j.icarus.2014.12.034.
- Montabone, L., K. Marsh, S. R. Lewis, P. L. Read, M. D. Smith, J. Holmes, A. Spiga, D. Lowe, and A. Pamment. 2014. "The Mars Analysis Correction Data Assimilation (MACDA) Dataset V1.0." *Geosci. Data J.* 129-139. doi:10.1002/gdj3.13.
- Navarro, T., F. Forget, E. Millour, and S. J. Greybush. 2014. "Detection of detached dust layers in the Martian atmosphere from their thermal signature using assimilation." *Geophys. Res. Lett.* 6620-6626. doi:10.1002/2014GL061377.
- Read, P. L., S. R. Lewis, and D. P. Mulholland. 2015. "The physics of Martian weather and climate: a review." *Rep. Prog. Phys.* doi:10.1088/0034-4885/78/12/125901.

- Ruan, T., L. Montabone, P. L. Read, and S. R. Lewis. 2012. "Assimilating and Modeling Dust Transport in the Martian Climate System." *Formation, Detection, and Characterization of Extrasolar Habitable Planets: Proceedings IAU Symposium No. 293*. doi:10.1017/S1743921313013094.
- Ruan, T., R. M. B. Young, P. L. Read, S. R. Lewis, and L. Montabone. 2017. "Regional and global dust storms on Mars investigated using data assimilation." *Sixth International Workshop on Mars atmosphere modelling and observations*. Granada, Spain.

Investigating the role of advection processes in improved Martian dust assimilation techniques for ExoMars

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Introduction

- Mineral dust has a central role in the Martian meteorological system, analogous to water on Earth. Atmospheric dust interacts with solar radiation, affecting the global circulation and dust lifting mechanisms in complex feedback loops.
- Martian dust storms can rapidly reach global scale, last weeks, and cause greater temperature variations than on Earth [1].
- Understanding Martian dust and its behaviour is therefore key for future activity on Mars. A valuable tool for this is data assimilation using the LMD-UK Mars Global Circulation Model (MGCM).

Atmospheric modelling and data assimilation

- Mars satellite data, such as from Thermal Emission Spectrometer (TES), can be integrated into the MGCM with data assimilation, constraining the model for the best possible atmospheric representation [2].
- The Open University's data assimilation uses an analysis correction scheme adapted from the Met Office [3]: each observation corrects each model point by a factor related to their temporal and spatial separation.
- Most data assimilation schemes use prescribed exponential distributions to represent the vertical structure of dust [6]; however, recent observations have revealed discrete dust layers in the upper atmosphere [4].
- MCS is the only current instrument to measure vertical dust profiles, and recent work has assimilated these jointly with column data to produce improved models [10].
- However, MCS retrievals do not include data from below 8 km above the surface [5]; whereas most dust lies in the bottom 5 km. This limits (for example) observations of nascent dust storm profiles.
- Dust advection in this assimilation uses persistence forecasting [7]; others use averaging [8] or vary the dust field seasonally. Only recently have assimilation schemes started to include realistic dust transport.
- Fig. 1: dust visible optical depth (OD) from MGCM, TES assimilated (top) at $L_s=300$, MY 26; TES OD.

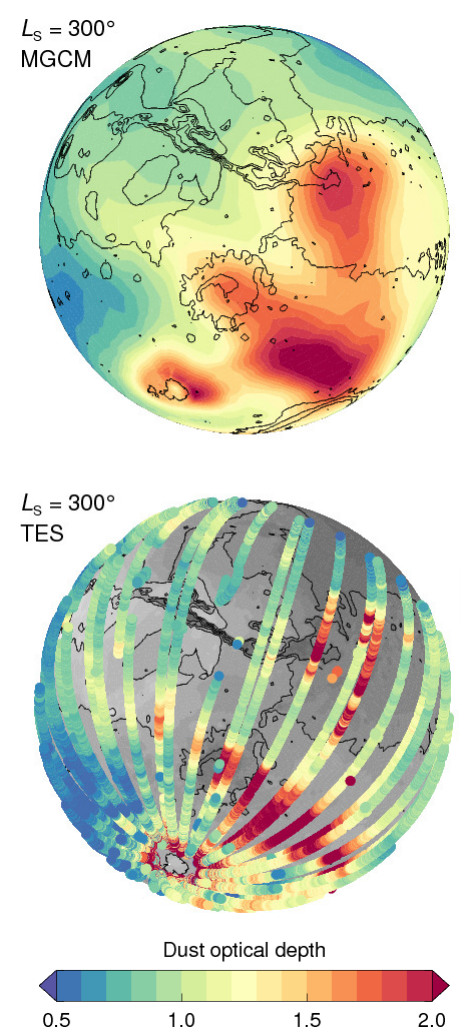


Figure 1: See text.

Dust Assimilation

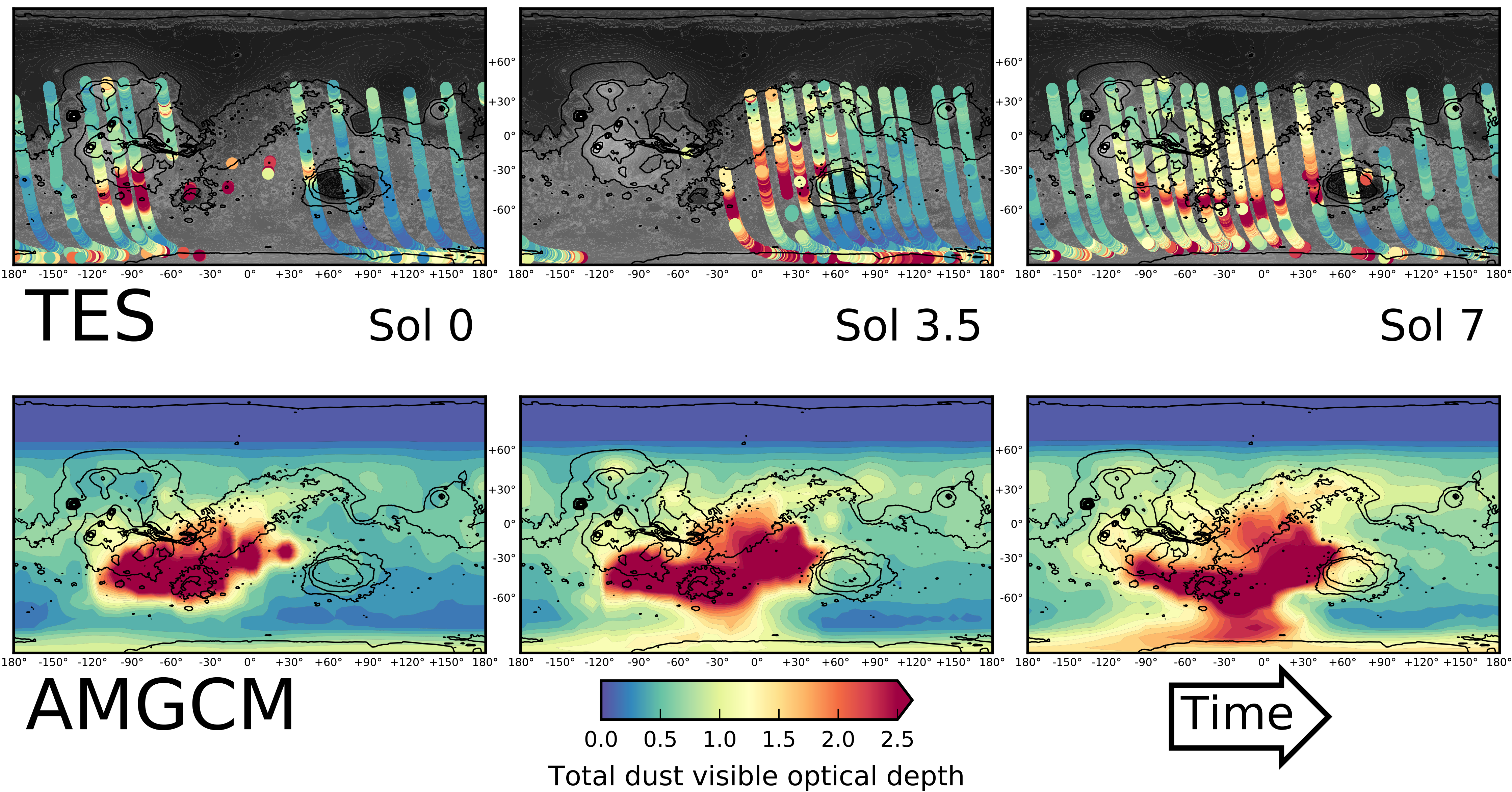


Figure 2: Top panel: total dust visible optical depth observations from TES over a 7.2-sol period centred on $L_s \sim 320$, MY 26. Bottom panel: total dust visible optical depth output for MGCM with TES dust data assimilated over the same period. The grey shading indicates topography.

- Fig. 2 compares TES observations of a C-type storm [9] with an assimilated simulation. The observations are irregularly distributed, leading to spatio-temporal blind spots, and only contain information on pressure, temperature and column dust opacity. Assimilation provides a more accurate representation of the atmospheric state than simple interpolation.
- The applications of dust assimilated models are significant. By giving us a continuous representation of the atmosphere, assimilation allows us to track the genesis and evolution of Martian dust events, as in Fig. 2. The assimilated model shows the dust event moving towards the south pole, something not captured in the raw observations alone.
- Using the MGCM also enables the derivation of important atmospheric variables such as wind speeds. In this way, assimilation takes patchwork observations and, by combining them with our best physical models, provides us with physically self-consistent and complete, 4-dimensional representations of the Martian atmosphere.

Future work

- Recent work by Ruan [11] and others on more realistic dust assimilation schemes has been promising in demonstrating hard-to-replicate results, such as detached dust layers.
- Future work will aim to further improve advection in assimilation and maximise utility of observations: e.g. investigating how to couple model winds and dust distribution (Fig. 3.)
- These schemes will be tested on the MGCM using existing dust observations and compared with current schemes.
- This work aims for eventual use on observations from the ExoMars Trace Gas Orbiter (TGO), which from March 2018 will offer high-resolution vertical profiles of Martian atmospheric dust down to the surface.

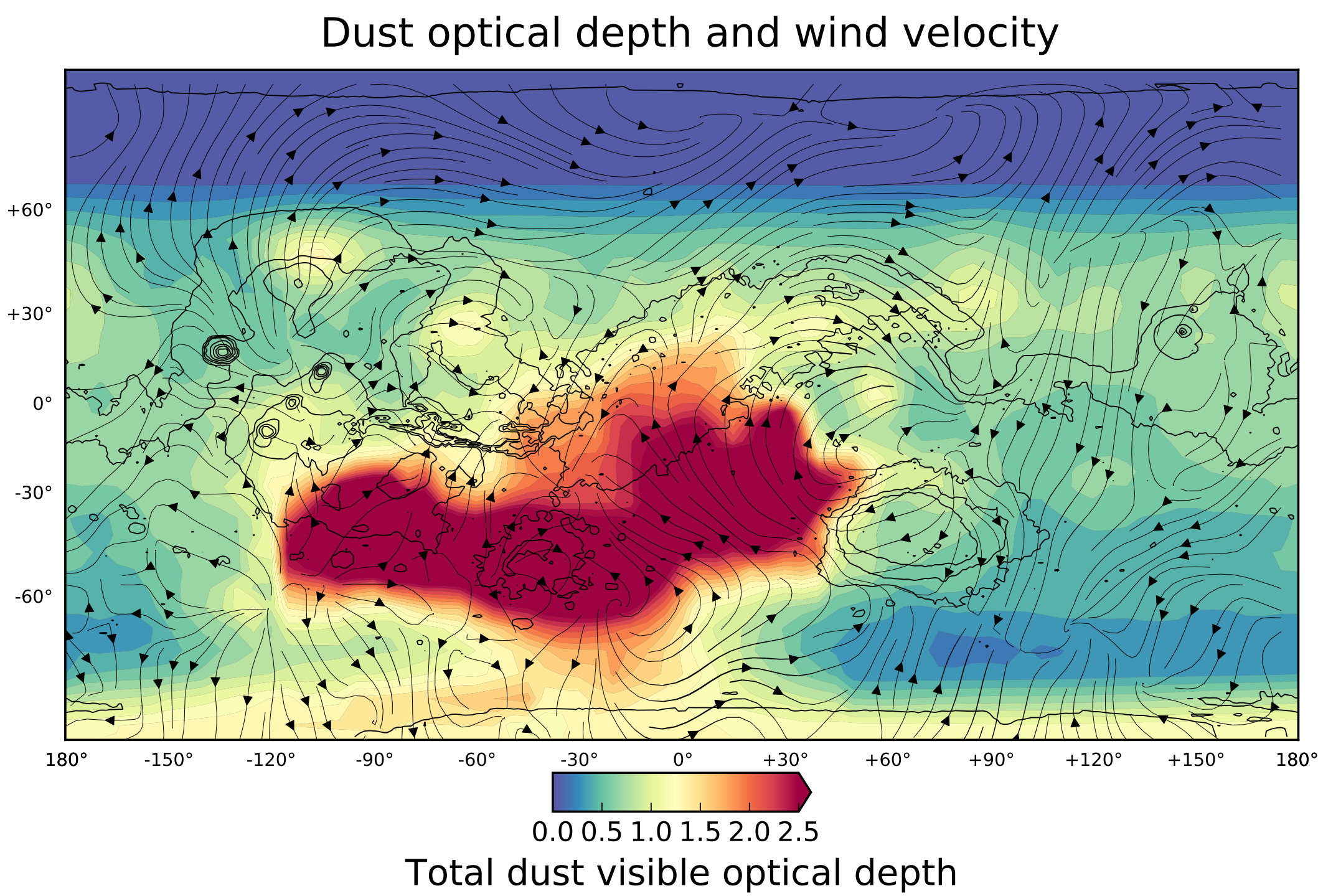


Figure 3: Total dust visible optical depth output and wind velocity at model height 5 metres for MGCM with TES dust data assimilated at $L_s = 320$.

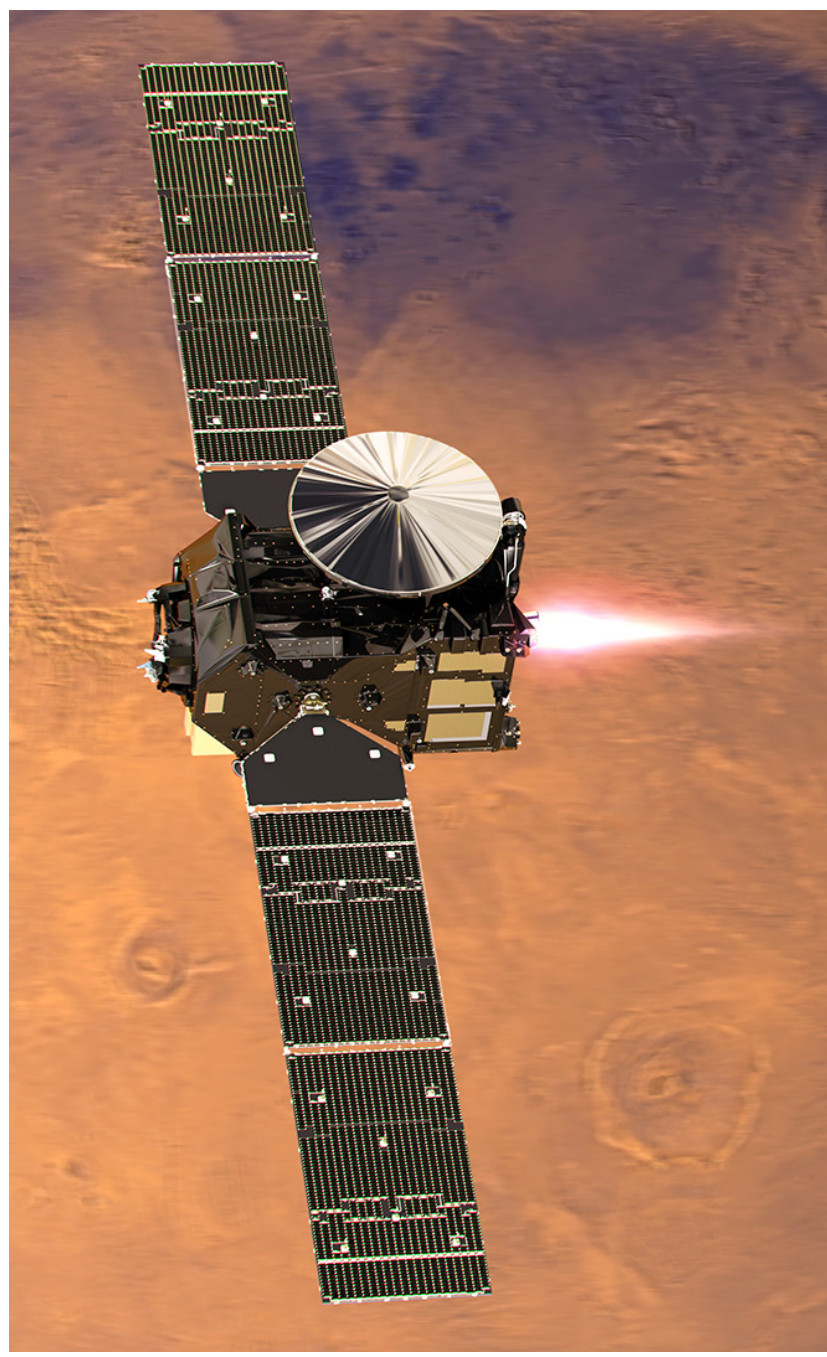


Figure 4: ExoMars TGO. Credit: ESA.

Summary

- Data assimilation is a crucial tool for providing our best representations of the Martian weather and climate system, and its key component of mineral dust.
- Improved dust assimilation methods allow for better use of existing observations and replication of observed atmospheric phenomena.
- Assimilation of more data, including vertical profiles, also has significant effects on model accuracy.
- This project aims to improve the treatment of dust transport within an assimilation scheme to obtain more realistic models.
- These improved techniques will be tested on existing vertical and column data with a view to use on new TGO data.

References

[1] R. Haberle et al., *Icarus*, (1982). doi:10.1016/0019-1035(82)90129-4
[2] W. Lahoz et al., *Data Assimilation*, Springer, (2010).
[3] A. Lorenc et al., *Q.J.R. Meteorol. Soc.*, (1991). doi:10.1002/qj.49711749704
[4] Heavens et al., *J. Geophys. Res. Planet.*, (2014). doi:10.1002/2014JE004619
[5] Heavens et al., *J. Geophys. Res. Planet.*, (2011). doi: 10.1029/2010JE003691
[6] B. Conrath et al., *Icarus*, (1975). doi:10.1016/0019-1035(75)90156-6
[7] S. Lewis et al., *Icarus*, (2007). doi:10.1016/j.icarus.2007.08.009
[8] L. Montabone et al., *Icarus*, (2015). doi:10.1016/j.icarus.2014.12.034
[9] D. Kass, *Geophys. Res. Lett.*, (2016). doi:10.1002/2016GL068978
[10] T. Ruan et al., *Proc. IAU Symp.* 293, (2012). doi:10.1017/S1743921313013094
[11] T. Ruan, *DPhil thesis*, (2015).

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